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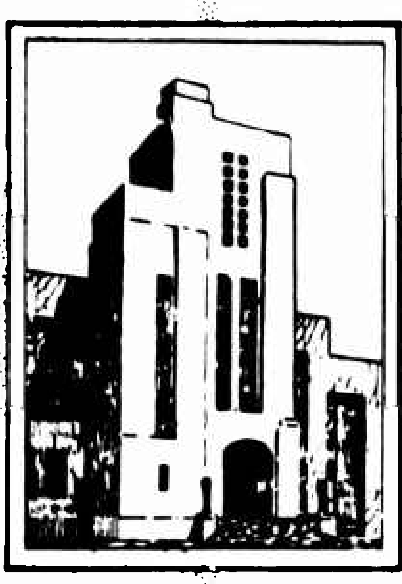

DEPARTMENT OF THE NAVY

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HANDLING QUALITY CRITERIA FOR SURFACE SHIPS

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HANDLING QUALITY CRITERIA FOR SURFACE SHIPS

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David Taylor Model Basin

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ABSTRACT

The concept of definitive maneuvers is introduced as a means for providing numerical measures of handling qualities of surface ships which can ultimately lead to objective standards and specifications. Data derived from three basic types of definitive maneuvers, the spiral, overshoot, and turning circle, are presented to indicate the extent to which handling qualities differ among existing ship types that have been evaluated. Tentative criteria are proposed to serve as interim standards for selected qualities until more complete and systematic data become available. It is recommended that the effort to accumulate data be expanded to include numerical measures of a wider variety of handling qualities not only for existing ships but for research designs with near optimum stability and control characteristics.

INTRODUCTION

The subject of handling qualities of surface ships in its broadest sense deals with all types of responses of a given ship resulting from its own controls and external disturbances. The active controls of a ship consist primarily of its rudders and propellers, although some ships may be equipped with fins, tanks, or gyroscopes for actively stabilizing roll and pitch responses. The external disturbances arise from either environmental conditions such as wind, waves, and water currents or interaction effects due to passage within restricted channels or proximity to other ships.

It may be stated that the broad objective in the field of stability and control of ships is to achieve the best stability and maneuverability characteristics commensurate with other design requirements. It is not always obvious, however, what is categorically the "best" as in some other fields of naval architecture. Many of the previous attempts to define these elusive qualities have been highly subjective and wrapped up in the lore of the experienced ship operators. Furthermore, judgments are usually made after delivery and long term use of a ship rather than on the basis of predetermined goals.

It is evident, therefore, that there is a pressing need for a system of objective standards whereby desirable handling qualities for various ship types can be ascertained and rated both from the standpoint of the designer and operator. Since such standards represent the finite objectives to be achieved by the design process, the handling quality approach should serve as a foundation and actually precede all other approaches in the field of stability and control of ships.

The researchers have traditionally employed indices, derivatives, and hydrodynamic parameters to analyze stability and control characteristics. These methods may serve a very useful purpose as analytical tools and

undoubtedly contribute to the overall picture. Their weakness lies in their use as figures of merit since they usually lead to qualitative interpretations such as "acceptable" or "unacceptable." Furthermore, a profound knowledge of mathematics and systems analysis of the type found only among the highly specialized is required to fully understand the implications of such analyses. The operators, on the other hand, are concerned more intimately with ship behavior as it really exists in point of full-scale time and environmental forcing functions. The operators are the customers and must live with the ship long after the design has left the drafting table and research laboratory. Thus to establish an effective system for defining handling qualities, it is necessary to bridge this gap to enable a meeting of the minds of the researcher, designer, and operator.

The steps to be taken in dealing with the subject of handling qualities logically appear to fall in the following sequence:

1. Identification of significant handling qualities for various types of ships,

2. Formulation of test procedures or techniques to reveal these qualities in a quantitative or numerical sense,

3. Collection of handling quality data from full-scale trials and free-running-model tests of existing ships which are considered to be representative of the compromises that have been made between handling qualities and other design considerations,

4. Collection of handling quality data from model tests of research designs to establish the extent to which improvements can be realized over existing types,

5. Development of tentative handling quality criteria for assessing relative merit among existing and proposed designs, and

6. Establishment of handling quality specifications to be incorporated in the contractual negotiations for new ships.

Although the importance of establishing an effective system for rating handling qualities has been stressed, it should be borne in mind that this is only a first step toward achieving the ultimate refinement of the subject. Once it is clearly understood by all concerned what handling qualities are desirable and possible, the next obvious question is what must the designer do to realize these predetermined qualities? A well-rounded program on the stability and control of surface ships should include the following elements:

1. Studies of the handling qualities

2. Analytical studies of the equations of motion to determine effects of arbitrary changes in parameters or coefficients

3. Experimental studies to relate geometric variations to hydrodynamic forces and moments acting on bare hulls, control surfaces, and other appendages either singly or in combination

4. Theoretical studies of the basic mechanisms of the generation of hydrodynamic forces and moments acting on bodies moving through fluids

5. Analog computer or free-running model studies of complete configurations utilizing the data obtained in items 1 through 4.

A complete treatise covering all of the aspects of handling qualities of surface ships would be extremely lengthy and somewhat premature. The subject of this paper is confined, therefore, to handling qualities associated with horizontal plane motions of surface ships in essentially still water. This includes the ground covered by the terminology of steering (course-keeping) and maneuvering (course-changing). The primary purpose of this paper is to formulate a system for numerically defining the most significant of these handling qualities to enable a meeting of the minds of the researcher, designer, and operator with the ultimate objective of achieving superior surface ships from the standpoint of stability and control. To carry out this purpose, a brief history of the work related to this problem is given to provide some background. The concept of "definitive maneuvers" is then introduced as the basic framework for establishing a system for rating handling qualities. The particular maneuvers selected for this purpose are described and numerical measures obtained from model and full-scale tests employing these maneuvers are given for a number of commercial-and naval-type surface ships. Criteria are established to indicate good practices on the basis of those ship designs which have been sampled. Obviously, these are only tentative criteria for surface ships in general and will be subject to change as more detailed and progressive information becomes available. Finally, recommendations are made concerning future studies and trends that may tend to improve the state of development.

HISTORY

The subject of stability and control of ships and other watercraft dates back to ancient times. In fact it is as old as the first and most primitive of watercraft. The importance of being able to steer and maneuver watercraft must have been obvious even to prehistoric man. It is difficult, therefore, to understand why progress in this field has been so slow and

haphazard throughout the centuries. An excellent survey of the historical development of design "procedures" for maneuvering is given by Saunders in the forthcoming third volume of his book on "Hydrodynamics in Ship Design".[1] Consequently, the background given herein is confined to highlights which pertain to the development of handling quality criteria.

The formal aspects of the subject of stability and control of ships embrace some of the most difficult problems in hydromechanics. It is understandable, therefore, why the researchers have been attracted by this challenge and have concentrated on basic studies involving analyses of the coefficients of the equations of motion. At the other extreme, designers, experimenters, and operators have been left to their own devices and have relied upon empirical rules of sometimes obscure origin to obtain ships whose handling qualities were at least tolerable. As the result of this "conflict in interest" the problem of establishing common goals has never been resolved. A few attempts were made in the past to survey experienced operators to obtain their opinions as to what handling qualities they would like to see in their ships. These opinions have been extremely vague and widely divergent even among masters of sister ships. When the operators retaliated by asking the designers and experimenters what handling qualities they could supply, the answers were equally vague and noncommittal. On the basis of such experiences, it now appears that one of the first hurdles that must be overcome is the establishment of a common language to describe and precisely define handling qualities.

Most of the papers which give a modern treatment of the subject of stability and control of ships were issued after the year of 1940. It is of interest to examine a few of these in chronological order to determine the extent to which they coincide with the handling quality concepts outlined in this paper. One of the first papers which appears to be pertinent in this respect is Kempf's 1944 paper entitled, "Maneuvering Standards of Ships".[2] Here, the zig-zag maneuver is introduced as a method for defining a maneuvering "norm" for ships. A standard maneuver of this type was carried out with 75 different freighters. Both full-scale ships and models were used for these experiments. At first glance, this work appears to be directly applicable to the present concept since it attempts to provide a numerical standard of maneuverability for a given type of ship. It may be noted, however, that the yardstick employed for this purpose is the "period" of the particular zig-zag maneuver. It is believed that this period is an index which is of interest to people involved in making frequency response analyses rather than a quality which concerns the operator. Furthermore, this quantity is not definitive; a small period is not necessarily indicative of either good course-keeping or good course-changing ability.

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[1]References are listed on page 240.

However, the other data taken during the first half-cycle of the zig-zag maneuver such as time to reach execute, overshoot heading angle, and overshoot width of path are considered of more operational significance. These data could be quantitatively used as handling quality criteria. Unfortunately, the detailed data have not been published and have since been either lost or destroyed.

The paper "Turning and Course-Keeping Qualities," by Davidson and Schiff (1946)[3] appears by its title to be directly applicable to the present subject. In fact, its prologue suggests that numerical indices are needed so that both turning and ease of steering can be discussed in quantitative terms. The authors advocate that it is important to look into the experience of the past and inquire into what combinations have been realized in actual bodies, together with rudder sizes that have been needed. The main theme of the paper, however, is concerned with prediction techniques and tests to determine whether or not a ship is directionally stable rather than the handling qualities themselves.

The papers by Dieudonné[4] present another valuable tool which can be utilized in assessing handling qualities. Although, the spiral was first introducted as a maneuver which could be used to qualitatively determine whether or not a ship is directionally stable, it now appears that it can be quantitatively interpreted. The autnor in fact suggests that the results of such maneuvers could be used quantitatively to indicate the ease of steering a ship.

Recent papers by the Japanese, presumably dealing with steering and turning qualities of ships,[5,6] are concerned primarily with analysis and prediction techniques rather than the establishment of handling quality criteria.

Within the past three years, there has been a concerted effort directed toward the development of techniques and the accumulation of data for the purpose of establishing handling quality criteria for submarines. Naturally, this information is contained in classified reports. The concepts and techniques which have been developed are, in many cases, applicable to the surface ship problem, and in fact, were utilized in forming the underlying philosophy of this paper. Thus it can be said at the present time, that the approach to the problem is reasonably understood. The task that remains is to utilize this approach to collect sufficient data to support a system for rating the handling qualities of surface ships.

It is of interest to observe the progress made in the allied field of handling quality criteria for aircraft. A recent paper prepared by the North Atlantic Treaty Organization Advisory Group for Aeronautical Research makes the following statements concerning handling qualities of aircraft:[7]

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Maneuvers which define inherent qualities are considered preferable because they directly provide specific numerical measures from a single maneuver of a given type. Also, these measures are indicative of the maximum potentialities of the ship system without qualification as to the efficiency of the operator in executing the maneuver. On the other hand, maneuvers which define qualities associated with the complete system are much more cumbersome and time consuming. Such a maneuver must be repeated many times with several operators, possessing varying degrees of skill, to furnish data which then must be statistically analyzed to obtain the desired figures of merit. Nevertheless, there are cases where the latter type of maneuver must be used if certain handling qualities are to be directly manifested.

The qualities associated with course-keeping are illustrative of a case where the statistical approach might be used. These qualities result from an interplay between the ship system consisting of the man or automatic control, the directional stability of the ship, the rudder effectiveness, and the control mechanism characteristics, and the external disturbances provided by currents, wind, and waves. Since the whole ship system is involved, appropriate numerical measures can be obtained only by conducting statistical-type course-keeping maneuvers.

Numerical measures pertaining to the inherent directional stability of a ship can be simply obtained by conducting a single spiral maneuver of the type attributable to Dieudonné.[4] Thus, if it is assumed that the ship with the best directional stability characteristics potentially will have the best course-keeping qualities, the numerical measures from the spiral maneuver can be used in lieu of those from the statistical course-keeping maneuver. Up to the present time, it has been necessary to make this assumption since most full-scale surface ships have not been available for properly conducted course-keeping tests. The only other alternative for providing course-keeping data would be to use simulator techniques similar to those used to evaluate performance of submarines. Unfortunately, neither hydrodynamic data nor well-developed techniques are available yet to support such studies with surface ships.

To gain a fuller appreciation of the concept and purpose of definitive maneuvers, it is helpful to temporarily forget the existence of other analytical methods and detailed approaches used to solve stability and control problems. If this is done it can be readily seen that the end product desired from stability and control studies points to those kinds of handling qualities that are of interest to the ship operators. Furthermore, the emphasis should be on treating these qualities in a quantitative sense if there is to be any hope of achieving progressive improvements on future ships. As a matter of orientation, it is desirable to consider descriptively the kinds of qualities of interest. The following is a list, which is by no means all-inclusive, of kinds of handling qualities that the operators should reasonably expect from a surface ship:

1. The ability to maintain course with a small amount of heading error, course error, and rudder activity

2. The ability to initiate a course change rapidly

3. The ability to check a course change rapidly with small overshoots in heading angle and width of path

4. The ability to execute an efficient steady-turning maneuver with small tactical diameter, advance, and transfer

5. The ability to accelerate and decelerate rapidly yet retaining good control

6. The ability to maneuver in and out of harbors ahead and astern at slow speeds without tug assistance.

The quantitative measures obtained from definitive maneuvers which are used to describe qualities of the kinds given in the foregoing list are discussed in the next section. It is pertinent to the concept of definitive maneuvers, however, that such numbers be expressed dimensionally in terms of real time and distance. In this manner, the numbers can be maintained within the perspective of the operators. In addition, they will serve as a better basis for specifications since they can be checked directly in acceptance trials. If it is desired, however, to utilize these numbers in analyses involving different-sized ships, the dimensional values can be converted into nondimensional ones by the use of appropriate normalizing factors.

On the basis of the preceding considerations, a given maneuver can be classified as a definitive maneuver if it has the following characteristics:

1. It can actually be performed by a full-scale ship and is not merely a laboratory or analytical response technique.

2. It has salient features which can be expressed as quantitative measures of specific handling qualities of the type that lead to objective standards and finally to specifications which must be met prior to the acceptance of a ship.

3. If possible, it should accomplish its purpose with a minimum of specialized instrumentation and without using a disproportionate amount of full-scale trial time.

DESCRIPTION OF SELECTED MANEUVERS

A wide variety of maneuvers have been used in the past as definitive maneuvers and others might conceivably be used in the future. Obviously, many of these maneuvers involve similar modes of performance and to this extent overlap each other in defining certain types of handling qualities. Consequently, in selecting standard definitive maneuvers, one can go from one extreme by considering too few maneuvers and perhaps overlooking some important handling qualities to the other extreme by utilizing too many and thus overburden trial schedules and produce excessive amounts of data. In the present stage of development of handling quality criteria, the conservative approach would be to select more instead of less than the required minimum number of representative maneuvers. In this manner, there would be less risk of overlooking some handling qualities that might become important in the future and the opportunity to conduct trials on a given ship may not again present itself. In any event, the number of maneuvers conducted on any given set of trials will be compounded by the range of speeds (forward and backing) as well as other pertinent conditions. A thorough coverage of operational conditions should be considered in establishing handling quality criteria. It is unwise at this stage of development to place too much credence on handling qualities of a single type. This point has been confirmed by recent experiences with naval-type surface ships. For years, the maneuverability of naval ships was evaluated solely on basis of steady-turning tests. However, within the last few years it was found that some of the ships which had excellent turning characteristics had poor and, at least in one case, unacceptable directional stability characteristics. As the result of these findings, spiral tests to define directional stability characteristics have now become as standard with naval ships as the traditional turning tests.

The development of facilities, instrumentation, and techniques which are necessary for detailed treatment of the subject of stability and control of surface ships has been relatively slow. In addition, full-scale surface ships have been made available for only limited programs to evaluate maneuverability. Consequently, whatever data are available have been obtained from essentially three types of definitive maneuvers, spirals, overshoots, and turning circles. Each of these three types of maneuvers are discussed in terms of the purpose of the maneuver, the procedure followed in carrying out the maneuver, the numerical measures derived from it, and the significance of the numerical measures.

SPIRALS

The spiral is a definitive maneuver which is intended to provide quantitative measures of the inherent directional stability characteristics of a ship. These characteristics can be used to impute course-keeping potentialities. The maneuver can be conducted in a variety of ways with full-scale

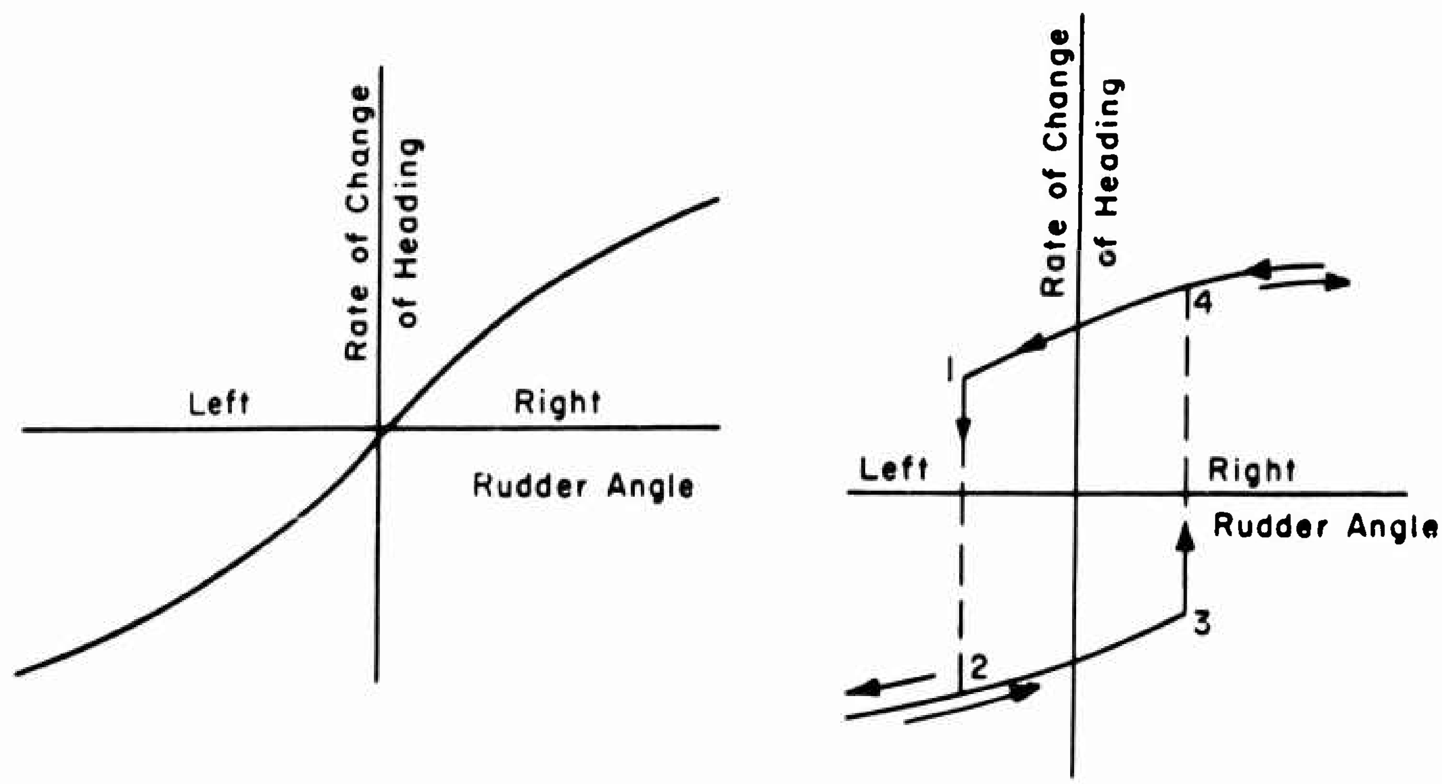
ships, free-running models, and analog computers utilizing hydrodynamic force and moment data derived from captive model tests. An attractive feature of the maneuver for full-scale tests is that it can usually be carried out with the ship's own instrumentation. The basic maneuver, which can be carried out when sea room is not at a premium, is conducted as follows:

1. The propeller speed is adjusted to an rpm corresponding to a predetermined speed (either ahead or astern). Once a steady rpm is achieved, the throttle settings are not changed for the balance of the maneuver.

2. The rudder is manipulated as necessary until a "practically" straight course has been obtained and held for one minute.

3. The rudder is then deflected to about 15 degrees right and held until the rate of change of heading as indicated by the gyro compass and a stop-watch remains constant for one minute. The rudder angle is then decreased by 5 degrees and held again until the rate of change of heading remains constant for one minute. The procedure is repeated until the rudder has covered a range of from 15 degrees on one side to 15 degrees on the other side and back again to 20 degrees on the first side. For 5 degrees on either side of zero or neutral rudder angle, the intervals are taken in one degree steps.

The numerical measures obtained from the spiral maneuver are the steady rates of change of heading versus rudder angles. A plot of these variables is indicative of the inherent characteristics of the ship. If the plot is a single continuous curve going from right rudder to left rudder, as shown in Figure 1a, the ship is said to be directionally stable. If, however, the plot consists of two branches joined together to form a "hysteresis" loop, as shown in Figure 1b, the ship is said to be directionally unstable. In addition, the size of the loop (height and width) can be used as a numerical measure of the degree of instability; the larger the loop, the more unstable the ship. The width of the loop is also a fairly direct indication of probable course-keeping ability since it defines the envelope of rudder angles which must be employed to keep the ship from swinging from port to starboard. Unfortunately, the spiral technique as presently used does not define the degree of stability for stable ships. The slope of the rate curve at the origin seems to be indicative of degree of stability for directionally stable ships. Also, the time required for the turning rate to decrease to zero when the rudder is returned to zero or neutral angle may provide a numerical measure of degree of stability. Further analysis of these techniques is required to establish these relationships, however, and it may develop that a supplementary definitive maneuver may be needed in the case of directionally stable ships.



(a) Stable Ship

(b) Unstable Ship

Figure 1 - Typical Curves from Spiral Maneuvers

OVERSHOOT

The overshoot is a definitive maneuver which is intended to provide quantitative measures of the inherent effectiveness of the rudder in making changes in heading or width of path. The kinds of handling qualities revealed by this maneuver are typified by the ability to initiate course changes and ability to check course changes during transient maneuvers. The maneuver can be conducted with full-scale ships, free-running models, and analog computers. The numerical measures pertaining to the heading changes can be obtained with the ship's own instrumentation. Numerical measures associated with width of path, however, will require either much more elaborate equipment than is generally available for most ships or testing on a range with triangulation facilities.

The overshoot maneuver is shown diagrammatically in Figure 2. It can be seen that if the maneuver is continued through several cycles it results in the well-known zig-zag maneuver. A typical procedure for conducting overshoot tests is as follows:

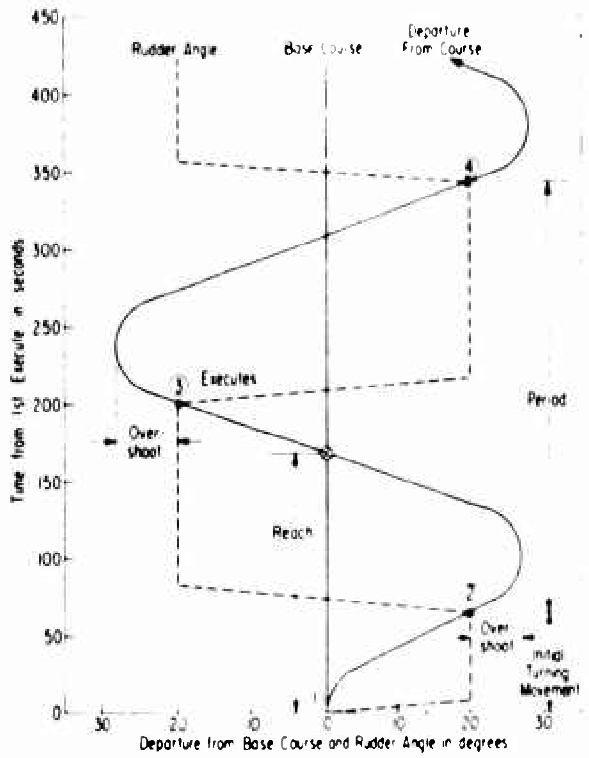


Figure 2 - Diagram of Overshoot Maneuver

1. The propeller speed is adjusted to an rpm corresponding to a predetermined speed and when a steady rpm is achieved, the throttle settings are not changed for the balance of the maneuver.

2. The rudder is manipulated as necessary until a "practically" straight course has been obtained and held for one minute.

3. After steady conditions on straight course have been established, the initial heading shown on the ships gyro compass is noted. The rudder is then deflected at maximum rate to a predetermined angle, say 20 degrees, and held until a predetermined execute change of heading angle, say 20 degrees, is reached.

4. At this point, the rudder is deflected at maximum rate to an opposite (checking) angle of 20 degrees and held until the ship passes through its initial course.

5. If a zig-zag is to be completed, the maneuver is continued until a second execute of 20 degrees to the other side is reached. Whereupon, the rudder is again deflected rapidly to an angle of 20 degrees in the first direction. This cycle is repeated through 3rd and 4th executes and so on.

The primary numerical measures obtained from the overshoot maneuver are the time to reach execute change of heading angle, overshoot heading angle, and overshoot width of path. The zig-zag maneuver provides the additional measures of reach and period which are perhaps more significant for frequency response analyses than establishment of handling qualities.

The time to reach execute is a direct numerical measure of ability to rapidly initiate changes in course. The heading and path-width overshoots are measures of course-checking ability and are indicative of the amount of anticipation and latitude of error that the helmsman is permitted if he is to remain within tolerable limits of the maneuver.

TURNING CIRCLES

The turning circle is a definitive maneuver which is intended to provide quantitative measures of the effectiveness of the rudder in producing steady-turning characteristics. The turning circle is the oldest, most familiar, and most widely used of the definitive maneuvers. The handling qualities defined by this maneuver are generally considered to be more important to naval than most sea-going merchant ship applications. The maneuver can be conducted with full-scale ships, free-running models, and ultimately with analog computers. As with the other maneuvers, some of the desired numerical measures can be obtained with the ship's own instrumentation in open sea. However measures pertaining to path data will require either much more elaborate ship-borne equipment or testing on a range with triangulation facilities.

Although the turning circle maneuver is familiar to most naval architects, it is shown diagrammatically in Figure 3 for purposes of completeness. The standard procedure for the conduct of such maneuvers is as follows:

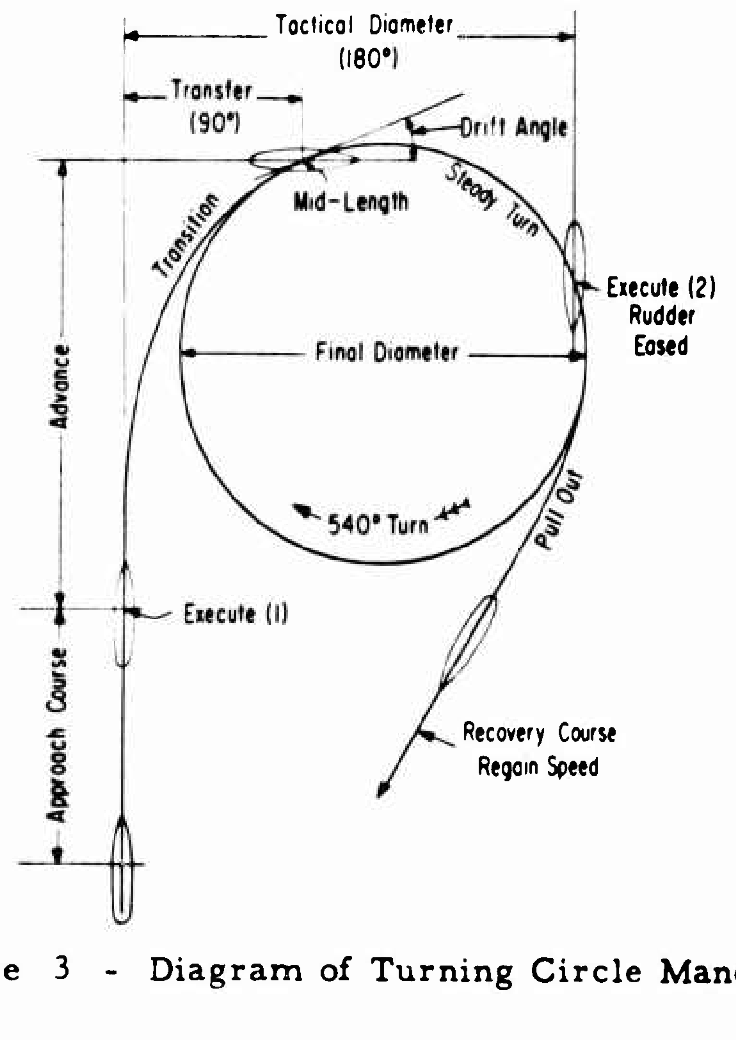


Figure 3 - Diagram of Turning Circle Maneuver

1. The propeller speed is adjusted to an rpm corresponding to a predetermined speed and when a steady rpm is achieved, the throttle settings are not changed for the balance of the maneuver.

2. The rudder is manipulated as necessary until a "practically" straight course has been obtained and held for one minute.

3. After steady conditions on straight course have been established, the initial heading on the ship's gyro compass is noted. The rudder is then laid to a predetermined angle, say 35 degrees, and held until a change of heading of generally at least 540 degrees has occurred at which point the maneuver is terminated.

The numerical measures obtained from the turning circle tests are the tactical and steady-turning diameter, advance, transfer, times to change heading 90 and 180 degrees, and loss of speed in turning. All of these measures should be taken into consideration in defining handling qualities associated with this type of maneuver.

NUMERICAL MEASURES FOR VARIOUS SHIPS

It has not been common practice in this country to carry out either full-scale maneuvering trials or model tests to evaluate handling qualities of commercial ship types.[8] In fact, it has only been in recent years that naval ship types have been tested to evaluate handling qualities other than those associated with turning circles. Consequently, there is only a limited amount of such data in existence. Furthermore, due to classification restrictions, only a small amount of the existing data is available for general publication. It is hoped, therefore, that enough interest in the problem will be generated to encourage ship owners to carry out the necessary tests with existing and new ships and thus contribute to the general fund of data on handling qualities of surface ships.

The geometrical characteristics and numerical measures obtained from definitive maneuvers of unclassified ships that have been tested by the David Taylor Model Basin are given in Tables 1 and 2, respectively. It may be noted that all values are given dimensionally to preserve their significance to the operators and thus comply with the concept outlined earlier in this paper. Sufficient data are given, however, to allow those who prefer to make an analysis on basis of nondimensional coefficients or ratios to do so. The designations A, B, C, etc., indicate the various different ships. Upper case letters are used when the data have been obtained from full-scale trials. Lower case letters are used when the data have been derived from free-running model tests.

TABLE 1

Geometrical Characteristics

Designation	Description	Length ft	Beam ft	Draft ft	Trim ft	Displacement ton	Rudder Area sq/ft
A	SS-SR*	435	63	22.75	3.5 aft	12,100	170
B	SS-SR	486	72	25.5	6.5 aft	15,100	292
C	SS-SR	475	72	18.63	6.1 aft	10,230	244
D	TS-SR	543	75	31.0	0 aft	24,275	314
E	TS-SR	525	75	26.25	1.0 aft	18,845	270
F	TS-SR	640	86	18.87	8.75 aft	19,000	392
G	TS-TR	500	82	17.0	4.0 aft	10,750	247
H	TS-TR and Sk	500	82	17.0	4.0 aft	10,750	247

*

Note: SS - Single Screw
SR - Single Rudder
TS - Twin Screw
TR - Twin Rudder
Sk - Skeg

TABLE 2

Numerical Measures from Definitive Maneuvers

Designation	Approach Speed knots	Spirals: Height of Loop degrees per second	Spirals: Width of Loop degrees	Overshoots: Time to Reach Execute seconds	Overshoots: Overshoot Heading Angles degrees	Overshoots: Reach seconds	Overshoots: Period seconds	Turning Circles: Tactical Diameter yards	Turning Circles: Advance yards	Turning Circles: Transfer yards	Turning Circles: Time to Reach 90 degrees seconds	Turning Circles: Time to Reach 180 degrees seconds	Turning Circles: Speed Remaining After 180 degrees knots
A	7.5	0	0	70* R	3.0	165	295						
	7.5	-	-	68* L	3.5	172	295						
	7.5	-	-	75 R	5.0	185	345						
	7.5	-	-	76 L	5.5	185	345						
	15.0	0	0	40* R	4.0	97	165						
	15.0	-	-	40* L	4.0	98	168						
	15.0	-	-	44 R	7.5	108	193						
	15.0	-	-	43 L	8.5	113	207						
a	7.5	0	0	71*	4.0	183	309						
	7.5	-	-	80**	6.0	190	310						
	7.5	-	-	71	7.5	183	333						
	15.0	0	0	37*	5.0	103	175						
	15.0	-	-	38**	6.5	104	179						
	15.0	-	-	39	9.0	103	184						
B	8.0	0	0	65*	3.0	160	260						
	8.0	-	-	70	5.0	185	315						
	12.0	-	-										
	12.0	-	-										
	16.0	0	0	37*	4.0	90	137						
	16.0	-	-	40	5.0	88	150						
	20.0	-	-										
	20.0	-	-										
b	14.0	0	0	35*	3.5	110							
	14.0	-	-	48	6.0	83	121						
C	10.0	0	0	55* R	4.5	125	195						
	10.0	-	-	50* L	4.0	125	206						
	10.0	-	-	50 R	7.0	128	227						
	10.0	-	-	47 L	7.0	128	229						
	12.0	-	-	27* R	4.0	[illegible]	135	695 R	565	320	119	234	6.5
	12.0	-	-	27* L	5.5	79	111	630 L	565	285	114	217	6.5
	17.0	0	0	34 R	10.0	91	158	735 R	600	340	93	178	10.9
	17.0	-	-	36 L	9.5	92	155	705 L	610	315	89	169	11.1
	21.5	-	-					[illegible]	635	355	76	142	13.4
	21.5	-	-					780 L	660	340	77	143	14.3
c	10.0	0	0	45* R	4.0	123	215						
	10.0	-	-	*47**	6.8	130	229						
	10.0	-	-	47	7.5	127	239						
	17.0	0	0	34*	5.0	89	148						
	17.0	-	-	43**	7.0	99	113						
	17.0	-	-	38	8.5	97	111						

Note: * 10-10 zig-zag
** 15-15 zig-zag

TABLE 2 (continued)

Numerical Measures from Definitive Maneuvers

Designation	Approach Speed knots	Spirals: Height of Loop degrees per second	Spirals: Width of Loop degrees	Overshoots: Time to Reach Execute seconds	Overshoots: Overshoot Heading Angles degrees	Overshoots: Reach seconds	Overshoots: Period seconds	Turning Circles: Tactical Diameter yards	Turning Circles: Advance yards	Turning Circles: Transfer yards	Turning Circles: Time to Reach 90 degrees seconds	Turning Circles: Time to Reach 180 degrees seconds	Turning Circles: Speed Remaining After 180 degrees knots
D	10.0	-	-					885	682	445	182	352	6.5
	15.0	-	-					875	655	465	122	235	9.7
	18.0	-	-					865	675	504	102	200	11.4
E	8.0	0.22	5.0	96*	4.0	238	535						
	8.0	-	-	100	9.5	275	490						
	16.0	0.58	5.0	60*	7.0	185	390						
	16.0	-	-	53 R	11.5	155	285						
	16.0	-	-	56 L	14.0	165	310						
e	8.0	0.24	6.4	93*	4.0	278	-						
	8.0	-	-	90**	5.0	250	-						
	8.0	-	-	93	7.0	252	-						
	16.0	0.42	2.5	53	7.0	169	-						
F	10.0	0.36	9.0	67	10.0	164	308						
	12.0	-	-	-	-	-	-						
	17.0	0.34	5.0	49	11.0	119	210						
	20.0	-	-	-	-	-	-						
f	10.0	0.14	3.0	77	6.5	177	308						
	17.0	0.22	4.5	56	10.5	135	220						
G	7.0	0.82	18+	71	28.0	261	-						
g	7.0	0.72	13.0	-	-	-	-						
H	7.0	0.26	4.0	97	11.0	236	-						
	7.5	-	-	77	10.0	195	344						
	15.0	-	-	43	20.0	123	209						
h	7.0	0.12	2.0	-	-	-	-						

Note: * 10-10 zig-zag
** 15-15 zig-zag

The numerical measures in Table 2 are derived from the spiral, overshoot, and turning circle maneuvers. The measures associated with the spiral maneuver are the maximum variation of steady heading rate at zero or neutral angle (height of hysteresis loop) and maximum variation of rudder angle at zero steady heading rate (width of loop). For directionally stable ships, both of these quantities become zero and beyond this point there is no further indication of "degree" of stability. The overshoot maneuvers are essentially zig-zag maneuvers conducted either with rudder angles of ± 20 degrees and execute heading angles of ± 20 degrees or rudder angles of ± 10 degrees and execute heading angles of ± 10 degrees. The former are considered to be more preferable for defining course-changing ability; the latter are directly comparable with Kempf's data. The measures taken during the first half cycle of the maneuver, namely time to reach execute and overshoot heading angle are considered to be most significant. However, the reach which is the time to complete the first half cycle of the heading trajectory and the period which is the time to complete succeeding whole cycles are also listed for comparative purposes. The numerical measures taken from the turning circle maneuver are the tactical diameter, advance, transfer, time to reach 90 degrees change of heading, time to reach 180 degrees change of heading, and loss of speed after 180 degrees change of heading. For any of the foregoing measures, the best performance is characterized by the lowest value. However, some of the qualities have a tendency to be conflicting and, therefore, it may not be possible for a given ship to have all of the lowest numbers among a comparable group of ships.

It is of interest to examine the range of pertinent handling qualities among the existing ship types that have been evaluated. This can be accomplished with graphs showing the individual numerical measures. Data available from other naval ships are included to make the survey as representative as possible. Since these data are classified, they are not identified or related to specific ships. The values for all ships considered have been corrected to correspond to a 500-foot version of each design to retain the dimensional characteristics without becoming involved in other ramifications. These values can be interpreted as applying with reasonable accuracy to ships between 300 and 700 feet in length.

The numerical measures from spiral maneuvers are presented by the bargraphs in Figure 4. To simplify the graphs, the height or width of the hysteresis loop for each ship was averaged over a range of ship speeds between 5 and 20 knots. The bars are constructed as percentages of the total number of the ships in the survey. It may be noted that more than one-half of the ships are directionally stable. Even though they are in active service, most of the remaining ships have characteristics which are not considered desirable on the basis of the standards that are being established. In a few isolated cases, the degree of directional instability is so great that the ships are difficult and hazardous to maneuver.

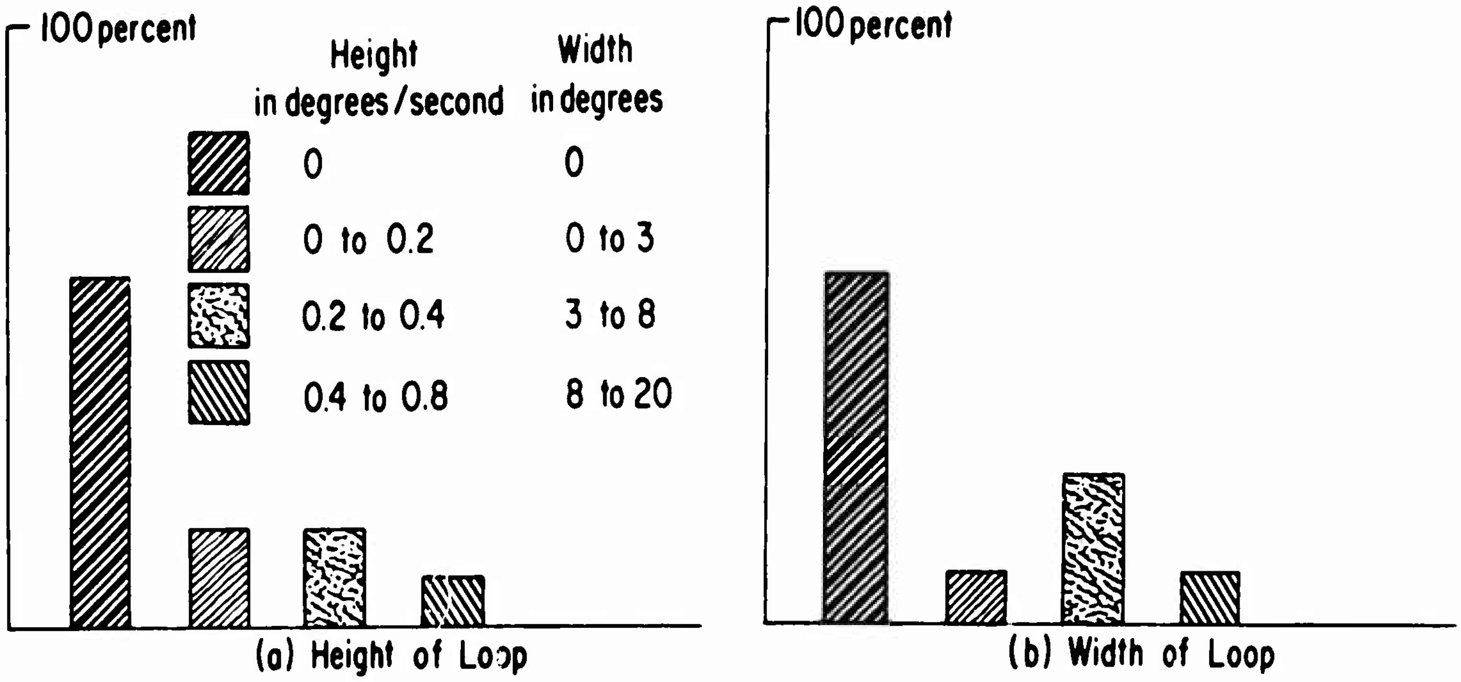


Figure 4 - Bargraph of Numerical Measures from Spiral Maneuvers

As mentioned earlier, it is not possible to assess the status of maneuverability of commercial ships. It may be reasonably inferred, however, that they will generally have somewhat poorer handling qualities than comparable naval ships since their operational requirements are not usually as severe.

Ships which have no loop as the result of spiral maneuvers should have good course-keeping ability. Those with a wide loop can be expected to require an excessive use of the rudder with attendant wear and tear on the steering machinery and fatigue of the helmsman. In addition, the excessive rudder travel will probably result in an increase in resistance and consequent increase in fuel consumption. It is believed that the foregoing predictions can be reasonably inferred from the spiral results. It would be desirable, however, to have course-keeping data for corroboration.

To illustrate the consequences of a high degree of directional instability, the case of one of the ships studied, a twin-rudder naval auxiliary, may be considered. On the basis of model turning tests, the ship was expected to have very good turning characteristics. Since it was not standard procedure at the time, model maneuvering tests were not conducted. Unfortunately after the ship was built, it exhibited an unhappy facility for running aground when negotiating a channel which led to the building yard. Upon delivery to the Navy, it became obvious that the maneuvering characteristics of the ship had to be improved. The results of full-scale spiral tests indicated a hysteresis loop (for a 500 ship) which was 0.82 degrees per second high and over 18 degrees wide. On the way to the open sea area, it was noted that the helmsman habitually used ± 15 degrees rudder angle for normal course-keeping in smooth seas. These large rudder angles may have been influenced to some extent by the lack of physical exertion required to spin the wheel. There is no doubt, however, that at least ± 10 degrees rudder angle was necessary to maintain course.

As a result of model tests, an enlarged skeg was designed and welded to the ship. The loop was reduced to 0.26 degrees per second high and 4.0 degrees wide. It was not practicable to install a large enough skeg to completely eliminate the loop, however, the resulting performance was sufficient to meet the operational requirements of the ship.

The numerical measures derived from overshoot maneuvers of the various ships surveyed, including the classified naval ships, are compared in Figures 5 and 6. The values in the figures have been adjusted to correspond to 500-foot ships. All values have been obtained from a 20-20 overshoot maneuver and consist of the time to reach 20 degrees execute change of heading using 20 degrees rudder angle and overshoot angle using a rudder angle of 20 degrees to check the swing.

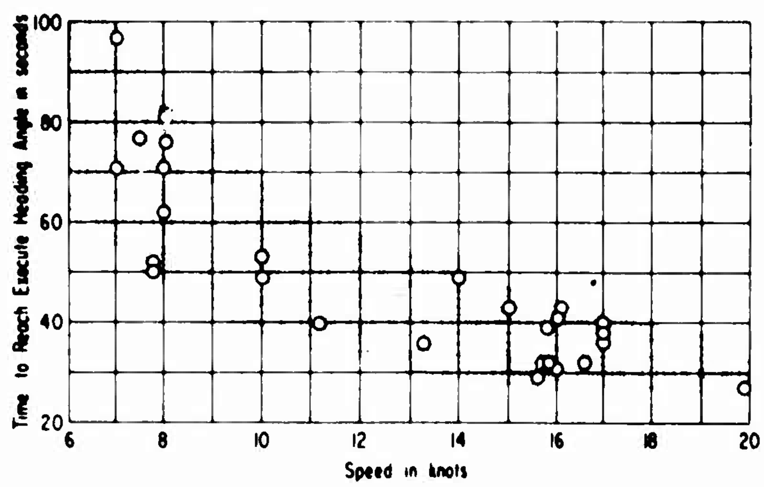


Figure 5 - Times to Reach Execute from 20-20 Overshoot Maneuvers

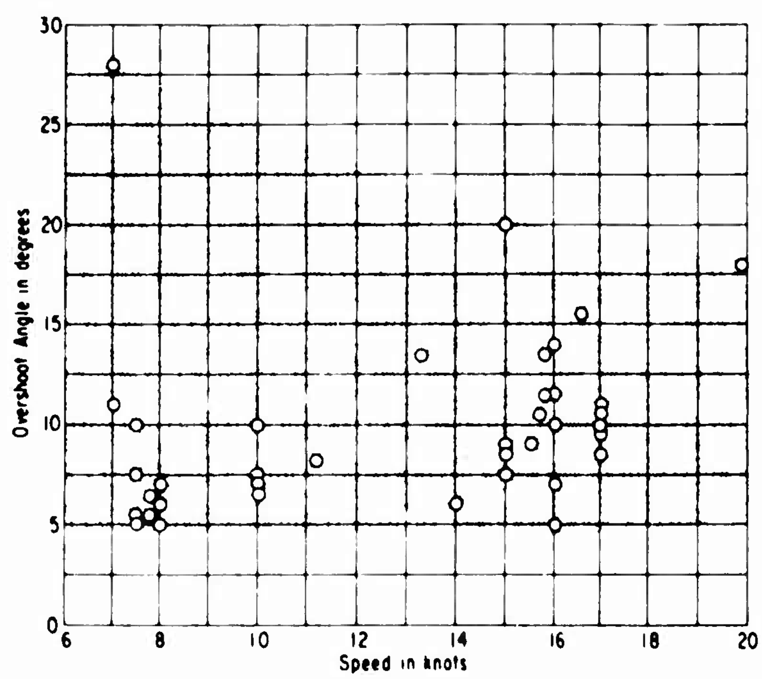


Figure 6 - Overshoot Angles from 20-20 Overshoot Maneuvers

The envelopes surrounding the spots in Figures 5 and 6 exhibit considerable spread among existing ships both in time to reach execute and overshoot angle. This suggests room for significant improvements in these respects and should serve as an incentive and challenge to the designers.

The rapidity with which a turn can be initiated (time to reach execute) appears to be determined primarily by the effectiveness of the rudder in providing turning moment to the ship. On the basis of an examination of the other characteristics of the ships corresponding to the spots on Figure 5, the directional stability does not appear to influence the time to reach execute. On the other hand, the ships with greater rudder effectiveness (those with rudders in the propeller race) appear to group themselves near the lower bound of the envelope curve for time to reach execute.

Figures 7 and 8 illustrate the effects of control effectiveness and directional stability on overshoot characteristics. Figure 7 shows trajectories from a 20-20 overshoot for two comparable naval auxiliaries. One of these ships is a twin-screw single-rudder type. The other is a single-screw single-rudder type with its rudder in the propeller slipstream. The latter is about 40 feet shorter but this difference in length is not considered significant. Although the twin-screw ship is somewhat unstable, this should not affect the comparison in regard to time to reach execute. The single-screw ship reaches 20 degrees execute, (2) in Figure 7, in 42 seconds whereas the twin-screw ship takes 56 seconds.

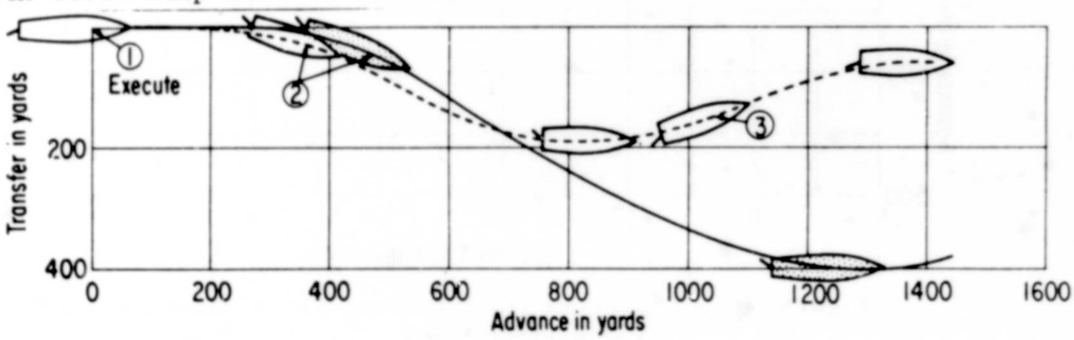


Figure 7 - Overshoot Trajectories of Two Different Types of Naval Auxiliaries

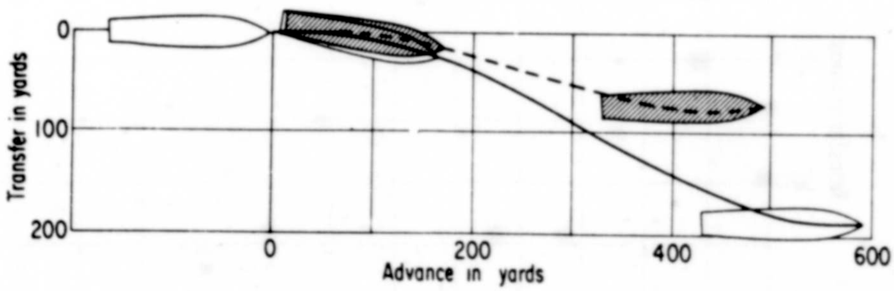


Figure 8 - Overshoot Trajectories of Twin-Screw Twin Rudder Naval Auxiliary with and without Centerline Skeg

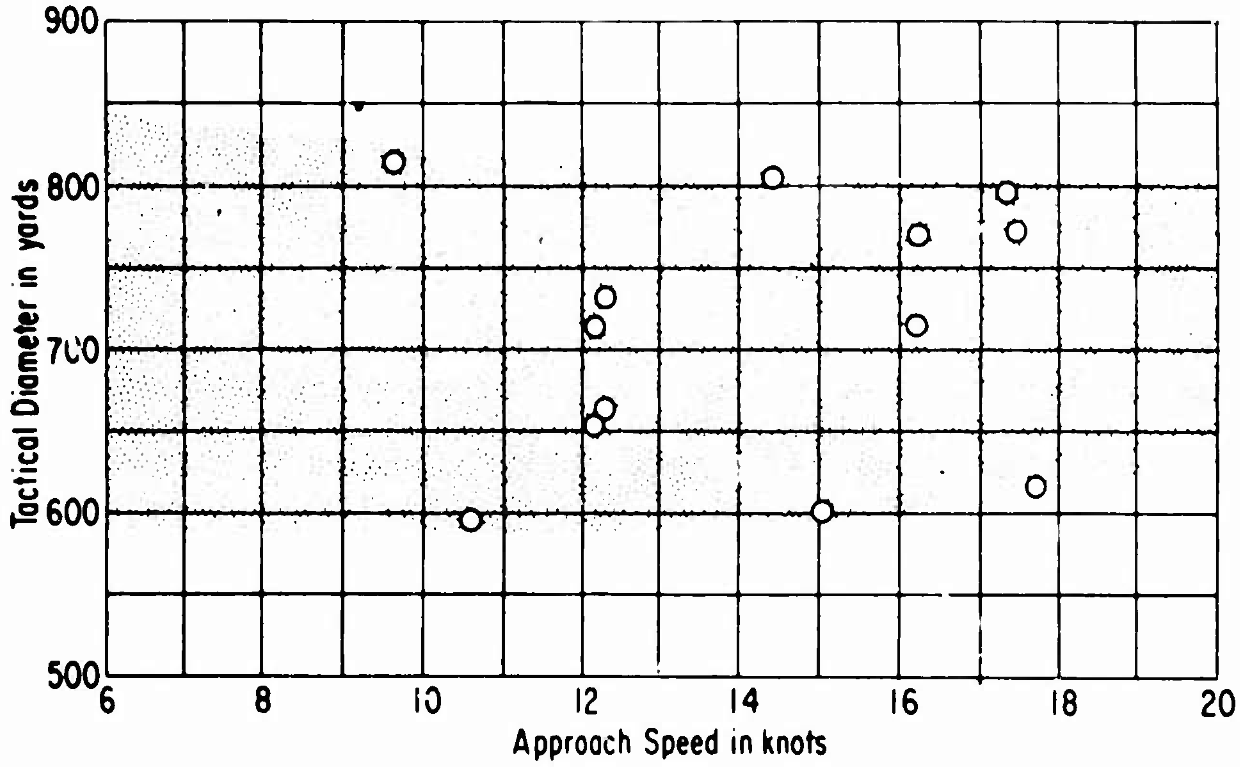


Figure 9 - Tactical Diameters from Turning Circle Maneuvers with 35 Degrees Rudder

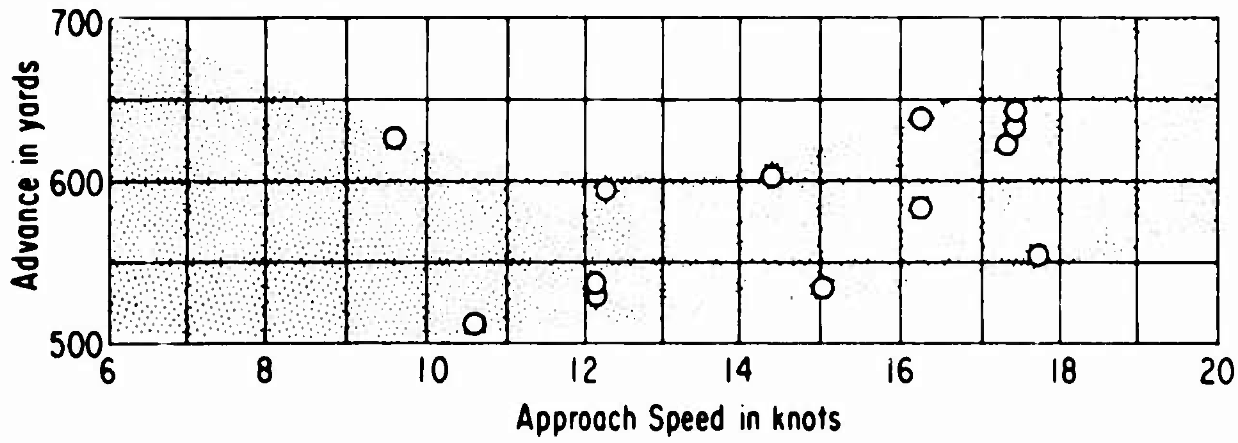


Figure 10 - Advances from Turning Circle Maneuvers with 35 Degrees Rudder

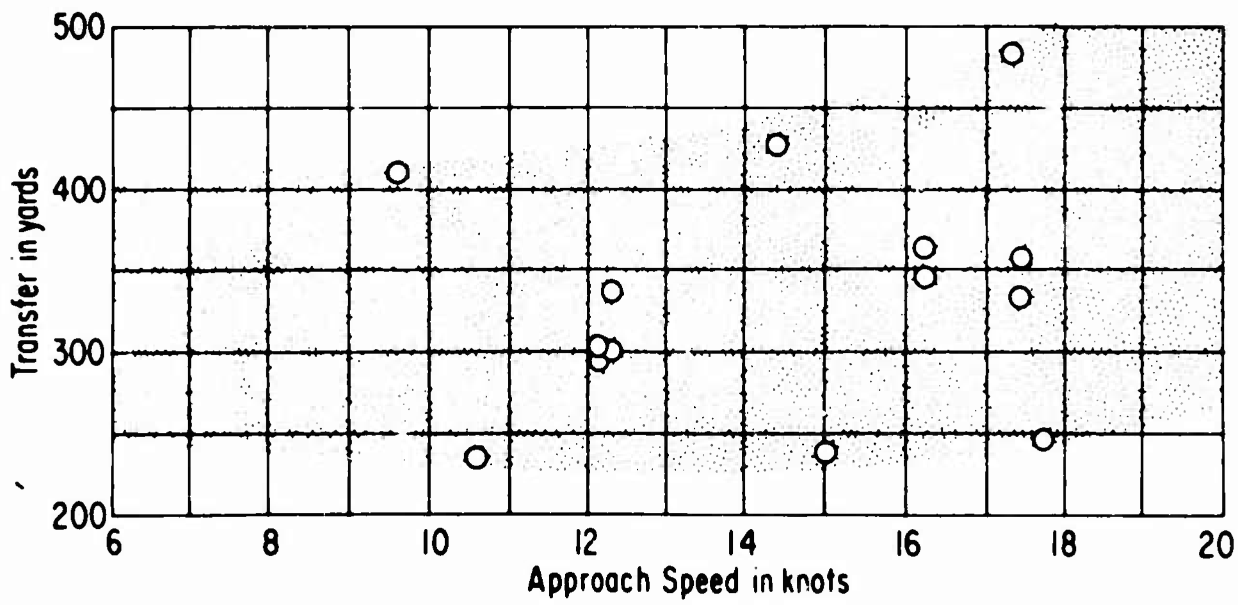


Figure 11 - Transfers from Turning Circle Maneuvers with 35 Degrees Rudder

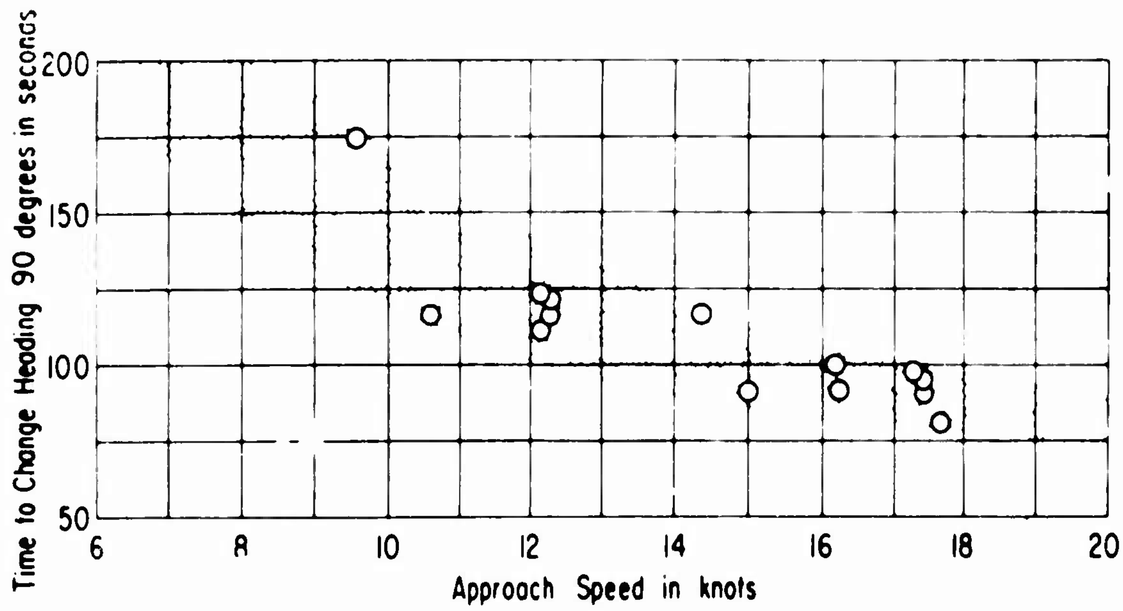


Figure 12 - Times to Change Heading 90 Degrees with 35 Degrees Rudder

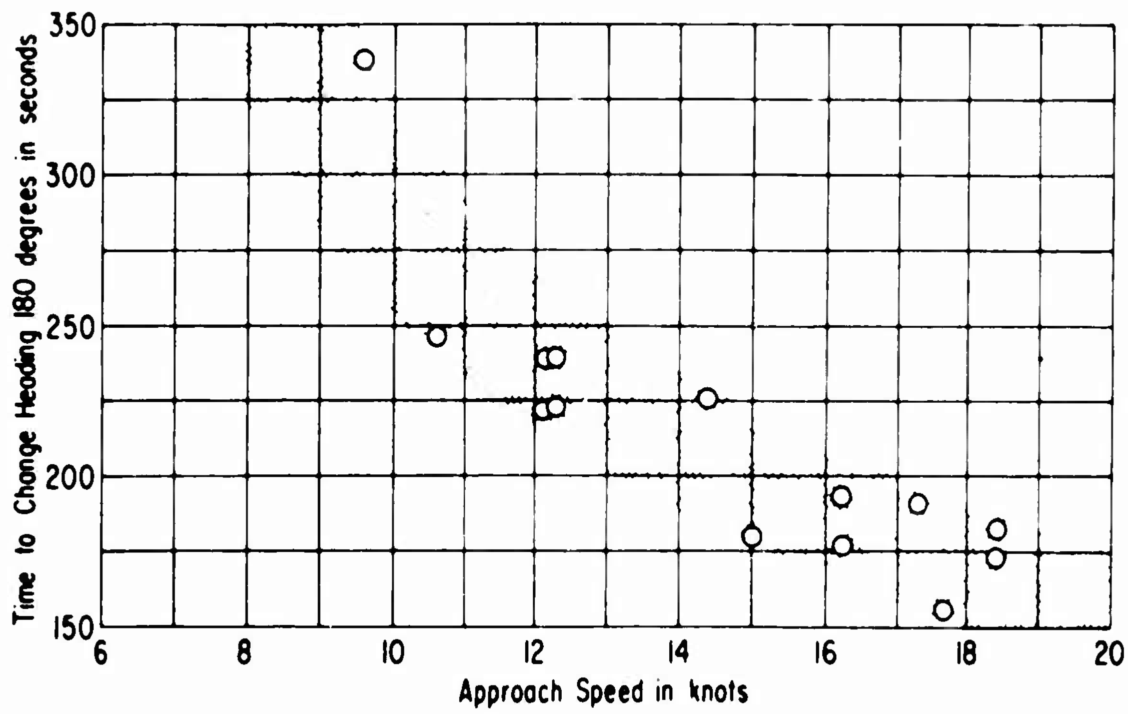


Figure 13 - Times to Change Heading 180 Degrees with 35 Degrees Rudder

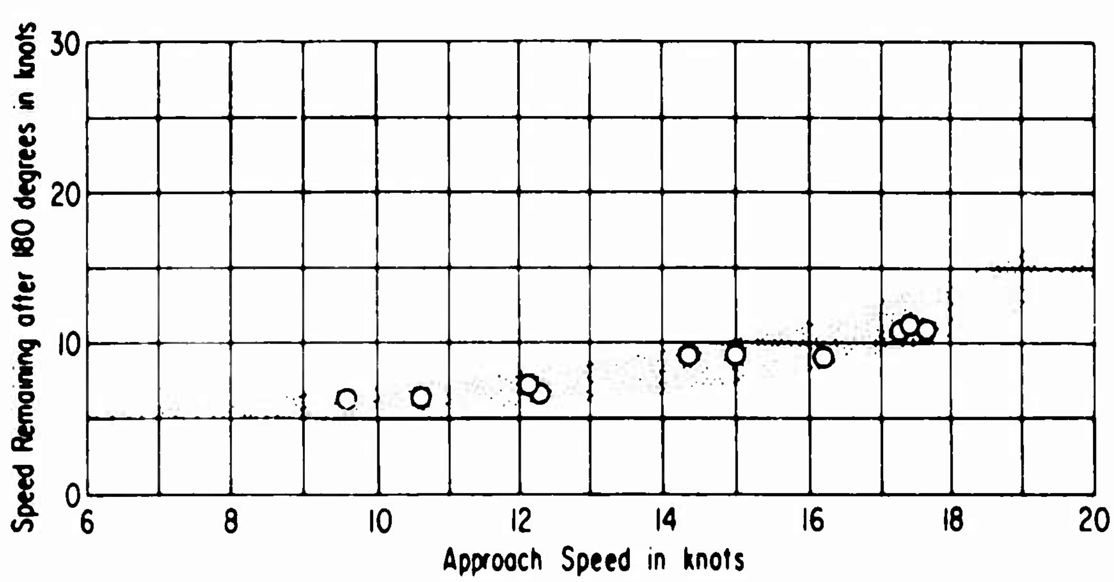


Figure 14 - Speeds Remaining after 180 Degrees Change in Heading from Turning Circle Maneuvers with 35 Degrees Rudder

The overshoot angles shown by Figure 6 appear to be affected both by directional stability and rudder effectiveness. It is difficult to say which of these factors has the strongest influence but it was noted that the excessively large overshoot angles were always obtained with the ships that had a high degree of directional instability. For example, in the case of the twin-rudder naval auxiliary whose directional instability was markedly decreased by addition of a skeg but whose rudder effectiveness was essentially unaltered, the overshoot angle was reduced from about 28 to 11 degrees.

As mentioned earlier, there are insufficient data available on overshoot width of path because of inadequate facilities for tracking. The width of path is of importance to the ship handler who is concerned with the path swept by the ends of the ship in checking course changes. This is particularly true in restricted waters and may mean the difference between damaging the ship or not. It is hoped that data of this type will be in more abundance after the new Maneuvering and Seakeeping Facilities at the Taylor Model Basin are put into operation. It is of interest at this time, however, to examine the effects of excessive directional instability on overshoot width of path for the case of the naval auxiliary mentioned in the preceding paragraph. Figure 8 depicts the results of overshoot maneuvers carried out with free-running models of the alternative designs using an execute change in heading of about 10 degrees with rudder angles ± 35 degrees. It may be seen that the overshoot width of path was reduced from about 175 to 65 yards by addition of the skeg. A similar overshoot test utilizing ± 20 degrees rudder was attempted with the highly directionally unstable ship but could not be completed within the width of the basin.

The advantage of realizing small overshoots can also be seen by reference to Figure 7. In this case, the total width of path changes from 400 to 190 yards for the comparable ships performing the same maneuver even though differences in directional stability are not too great.

The numerical measures from turning-circle maneuvers of the various ships surveyed are shown in Figures 9 through 14. Again, the comparisons are made on the basis of 500-foot ships. These figures demonstrate that, although turning circles have been studied more intensively than other maneuvering characteristics there is still a wide spread in turning performance among existing ship types. At first reaction, it appears that this can be explained on the basis of the different operational requirements for the various ships. The supposition may be made, for example, that the turning performance was sacrificed for the ships that must have excellent course-keeping ability. An examination of the various handling qualities among the ships surveyed does not support this contention. In fact, some of the tightest turning ships are directionally stable, and therefore, should have excellent course-keeping qualities as well. Conversely, some of the ships with the largest tactical diameters are directionally unstable and should exhibit poor course-keeping qualities.

In the past, the tactical diameter has been emphasized as the primary numerical measure of the effectiveness of a ship in turning circle maneuvers. It has been at least tacitly assumed that once the designer has exercised latitude in favor of a given tactical diameter, the values of the resulting quantities such as advance, transfer, times for heading changes, and speed remaining after 180 degrees are inevitable.[9] It is the philosophy of this paper to point out where ultimate refinements are possible rather than to compress the data into a rigid mold. Consequently, it is advocated that each of these numerical measures be scrutinized to see what improvements can be made in each without significantly affecting the others. For example, if a comparison is made on the basis of equal tactical diameter, it can be readily seen that among the ships surveyed there is a substantial spread in the values of advance, times for heading changes, and speed remaining after turning. Thus, there is evidence that the designer has some control over all of these qualities.

TENTATIVE HANDLING QUALITY CRITERIA

The numerical measures obtained from definitive maneuvers which have been presented herein constitute a relatively small sample of the handling qualities of existing ship types. Furthermore, the preponderant number of naval ships which, of a necessity, were included in the survey may affect interpretations when applied to merchant ship types. There is always a reluctance to make definite commitments or propose finite numbers, especially when a field of endeavor is in the formative stages. Nevertheless, some attempt should be made at this point to establish tentative criteria at least on those kinds of handling qualities covered by this paper. This may at least have the effect of familiarizing the profession with the use of the proposed rating system so that objective standards and specifications may emerge in the not-too-distant future.

It is fully realized that there are definite limitations and drawbacks to establishing criteria from insufficient data. It is hoped, however, that the tentative criteria will not be used too rigorously at this time as specifications or design objectives but rather as guides to good practices. In general, the tentative criteria which are proposed are pessimistic in the sense that it should be possible to do better when more detailed knowledge on the stability and control of ships becomes available. They may be optimistic, in the sense that they may not be fully realized with all ship types especially where the governing factors lie in other design considerations. In all cases, however, they should serve as guides for determining whether the price to be paid for achieving each and every number is reasonable in terms of the overall design.

For purposes of emphasizing the distinct modes of performance, the tentative criteria are grouped into those pertaining primarily to steering, maneuvering, and turning.

STEERING

In absence of adequate data from course-keeping maneuvers which could provide numerical measures of rudder activity, heading-angle deviation, and path deviation while maintaining course under specified environmental conditions, spiral maneuvers may be employed to provide reasonable measures from which steering qualities may be inferred. Complete elimination of the loop from the spiral is advocated in all cases to obtain a ship which is inherently directionally stable and tends to return to a straight path after a disturbance. The rudder angle is thus needed only to ensure that the path followed is on the desired course. As pointed out earlier, there is a unique turning velocity associated with any given rudder angle for stable ships whereas for unstable ships the direction the ship will turn is unpredictable within the bounds of the loop.

If it is not practicable to eliminate the loop entirely, every effort should be made to minimize both the height and width of the loop by suitable design of rudders and stabilizing surfaces. Any new design having a loop height exceeding 0.2 degrees per second (for a 500-foot ship) and a width exceeding 4 degrees should be examined very critically.

MANEUVERING

The ability to initiate and check moderate changes in course is one of the most important handling qualities of ships. The 20-20 overshoot maneuver provides an excellent measure of the inherent maneuvering ability of the ship. Two types of criteria for maneuvering are suggested, one for initial turning movement and the other for overshoot. On the basis of the 20-20 overshoot maneuver a 500-foot ship should reach execute heading angle in 65 seconds at 8 knots and 36 seconds at 16 knots. The nomograph in Figure 15 is provided to show criteria for sizes of ships between the range of 300 feet and 700 feet in length and 6 to 20 knots in speed.

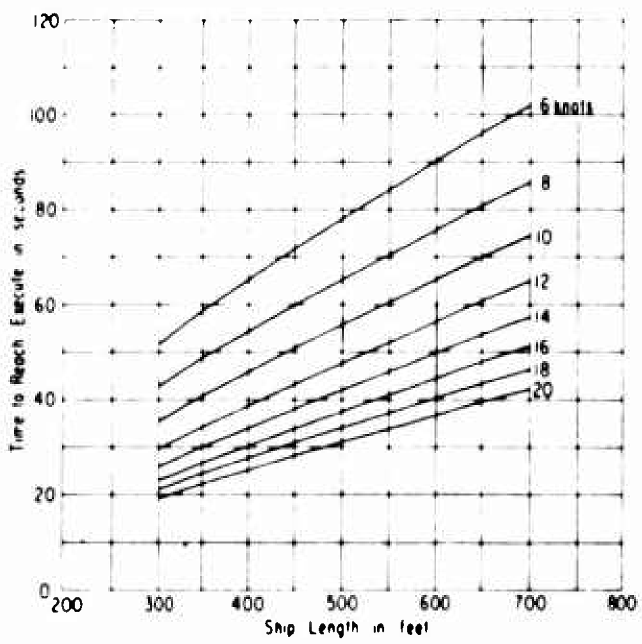


Figure 15 - Nomograph of Criteria for Time to Change Heading in a 20-20 Overshoot Maneuver

The overshoot angle does not vary with size of ship hence a nomograph similar to that for initial turning movement is not necessary. Overshoot angles of 5.5 degrees for 8 knots and 8.5 degrees for 16 knots are suggested as tentative criteria. Straightline interpolations for other speeds may be used as required.

TURNING

It is unrealistic to expect merchant ships to turn as tightly as combatant types of naval ships. Most of such modern naval ships strive for tactical diameter ratios of 3.25 ship-lengths or less with 35 degrees rudder angle. It is believed, therefore, that a tactical diameter ratio of 4.5 ship-lengths is a practicable criterion for merchant types and represents good handling performance objectives. Tactical diameters exceeding 7.0 ship-lengths reflect poor performance qualities and should be tolerated only under special conditions or requirements.

In dimensional terms, the criteria for tactical diameter and advance for various-sized merchant-type ships are shown in Table 3 for speeds of 8 and 16 knots using a rudder angle of 35 degrees.

TABLE 3

Turning Criteria

Ship Length feet	Tactical Diameter yards	Advance yards	Time to Change Heading 180 degrees seconds		Speed Remaining After Changing Heading 180 degrees knots	
			8 knots	16 knots	8 knots	16 knots
300	450	335	207	122	5	10
400	600	450	270	152	5	10
500	750	560	325	185	5	10
600	900	670	377	217	5	10
700	1050	785	428	250	5	10

RECOMMENDATIONS FOR FUTURE STUDIES

The advent of new and improved facilities such as the Rotating Arm and Maneuvering and Seakeeping Basins at the Taylor Model Basin should provide a stimulus for attacking problems in the stability and control of surface ships which have been neglected for centuries. With such facilities and the attendant advances that have been made in instrumentation and test techniques, it should be possible to study handling qualities much more intensively than has been done in this paper. Accordingly, it is recommended that a concerted effort be made to prevail upon the ship owners, shipbuilders, and model basins to accumulate data from definitive maneuvers, particularly on merchant ship types. Such definitive maneuvers should not only be of the type contained herein but should be designed to reveal the handling qualities of ships when subjected to the effects of environment, restricted channels, acceleration and deceleration, and other unusual circumstances.

It is further recommended that, concurrent with the effort to gain a firmer understanding of the status of handling qualities of existing ships, programs should be formulated with the purpose of achieving optimum handling qualities. Such studies can be carried out best in the model basins utilizing research designs where the emphasis will be on optimum stability and control to the exclusion, if necessary, of other characteristics. The advantage of utilizing such an approach is that the work can proceed with an understanding that the ship actually need not be built. It should be possible on this basis to determine what improvements in handling qualities are in store for ships provided that concessions to other requirements do not have to be made. In this manner, the various points of diminishing returns can be defined with reasonable clarity.

Once it is known how good the various handling qualities can be, the designer will be in a much better position to make decisions as to what compromises he is willing to make. It then remains to provide him with the fundamental hydrodynamic data and other design criteria to help him achieve his predetermined end result.

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REFERENCES

1. Saunders, H. E., "Hydrodynamics in Ship Design," Society of Naval Architects and Marine Engineers, New York (expected date of publication 1961) Vol. 3.

2. Kempf, G., "Maneuvering Standards of Ships," Deutsche Schiffahrts Zeitschrifft "Hansa", No. 27/28 (1944).

3. Davidson, K. S. M. and Schiff, L. I., "Turning and Course-Keeping Qualities," Society of Naval Architects and Marine Engineers Transactions, Vol. 54 (1946).

4. Dieudonné, J., "Collected French Papers on the Stability of Route of Ships at Sea, 1949-1950," David Taylor Model Basin Translation 246 (1953).

5. Inoue, S., "On the Turning of Ships," Memoirs of the Facility of Engineering, Kyushu University, Vol. 16, No. 2 (1956).

6. Nomoto, K., "Taguchi, T., Honda, K., and Hirano, S., "On the Steering Qualities of Ships," International Shipbuilding Progress, Vol. 4, No. 35 (1957).

7. Westbrook, B., and McRuer, D. T., "Aircraft Handling Qualities and Pilot Response Characteristics," Advisory Group for Aeronautical Research and Development, Report 125 (1957).

8. Schoenherr, K. E., "Steering," Chapter IV, Rossell, H. E., and Chapman, L. B., "Principles of Naval Architecture," Society of Naval Architects and Marine Engineers, New York (1939), Vol. 2.

9. Davidson, K.S.M., "On the Turning and Steering of Ships," Society of Naval Architects and Marine Engineers Transactions, Vol. 52 (1944) P. 292.